

Whether duration of the recovery phase of magnetic storm depends on the development rate of storm at its main phase?

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We compare dependences between the storm development rate $|Dst_{min}|/\Delta T$ (ΔT is the durations of main phase) and the duration of recovery phase of magnetic storms generated by three various types of interplanetary drivers: (1, 2) compression regions CIR and Sheath, and (3) body of interplanetary CME (magnetic clouds and Ejecta). Our analyze shows that the duration of recovery phase correlates with the storm development rate for CIR- and Sheath-induced storms, and does not correlate for ICME- induced storms.

1. Introduction

As has been shown by numerous papers, the dynamics of the magnetosphere during the development of magnetic storms significantly depends on the type of interplanetary driver (see, e.g., [Huttunen *et al.*, 2002, 2006; Borovsky and Denton, 2006; Pulkkinen *et al.*, 2007; Yermolaev *et al.*, 2010, 2012a; Guo *et al.*, 2011; Liemohn and Katus, 2012; Nikolaeva *et al.*, 2013; Cramer *et al.*, 2013] and references therein). These types of drivers are following: body of interplanetary CME (ICME) including magnetic cloud (MC) and Ejecta, and compression regions before high-speed solar wind stream (corotating interplanetary region – CIR) and before ICME (Sheath) (see, e.g., [Gosling, 1993; Gonzalez *et al.*, 1999; Yermolaev *et al.*, 2005]). Recently we showed that the dynamics of recovery phase of magnetic storms depends on the interplanetary driver types [Yermolaev *et al.*, 2014]. In particular we found that the durations of the main phase and the recovery phase correlate for CIR- and Sheath-induced storms and there is no dependence for these durations for MC- and Ejecta-induced storms. In this brief paper we will analyze data in details and give a physical interpretation of this result.

2. Methods

We use the same data set that we used in our previous papers [Yermolaev *et al.*, 2012b, 2014]: the measurements of Dst index (see <http://wdc.kugi.kyoto-u.ac.jp/index.html>) and our catalog of large-scale interplanetary events for the period of 1976–2000 (see the web site <ftp://www.iki.rssi.ru/pub/omni> and paper by Yermolaev *et al.* [2009]), prepared on the basis of OMNI dataset of interplanetary plasma and magnetic field parameters (see <http://omniweb.gsfc.nasa.gov>) and paper by King and Pap-

itashvili [2004]). The detailed description of the technique of the solar wind classification and comparison to magnetic storms is provided in several papers [*Yermolaev et al.*, 2009, 2010, 2012a, b].

Method of determination of durations of the main and recovery phases is schematically shown in Figure 1. To consider the existence of fast (initial) and slow (second) parts of the recovery (see, e.g., [*Gonzalez et al.*, 1994]), we calculate two durations: the initial time interval from the minimum of the Dst index up to $(1/2)Dst_{min}$ ($\Delta t_{1/2} = t((1/2)Dst_{min}) - t(Dst_{min})$) and $(1/3)Dst_{min}$ ($\Delta t_{1/3} = t((1/3)Dst_{min}) - t(Dst_{min})$), respectively. Analysis of the two durations $\Delta t_{1/2}$ and $\Delta t_{1/3}$ allows us to compare the durations of the fast and slow parts of the recovery phase.

3. Results

In our previous paper [*Yermolaev et al.*, 2014] we studied the durations of main ΔT and recovery $\Delta t_{1/2}$ and $\Delta t_{1/3}$ phases of storms induced by different interplanetary drivers and found the anticorrelation for CIR- and Sheath-induced storms. It is naturally to suggest that all durations depend on the magnitude of storms. However, the selection of data on the storm magnitude decreases the number of events and accuracy of analyze, and did not allow us to make reliable conclusions. So, we study a new variable $|Dst_{min}|/\Delta T$ which includes both duration ΔT and storm magnitude Dst_{min} , and is an average temporal derivation of Dst index or a storm development rate.

Figure 2 presents the dependence between the storm development rate $Dst_{min}/\Delta T$ and the fast and slow durations of recovery phase ($\Delta t_{1/2}$ and $\Delta t_{1/3}$) for different drivers. Three lower panels (from the bottom panel up) show individual events for Sheath-, CIR- and

ICME-induced storms, left and right coulombs present data for fast and slow durations. The straight lines through the data are linear fits to the points in the two-logarithmic scale (i.e., power law approximations of data). The top panels represent results of data fitting for the lower panels and allow one to compare them for various drivers. The correlation coefficients r for all panels are presented in Table. To emphasize the statistical significance of the results, we present the parameter $w = 0.5\sqrt{(N-3)\ln[(1+r)/(1-r)]}$ and probability P [Bendat and Piersol, 1971].

Sheath-induced storms have the most deep dependence between the storm development rate and both fast and slow durations. Despite a wide spread of points, these dependences possess rather high statistical significance (Probability $P = 90$ and 95 %). CIR-induced storms have similar parameters for fast duration $\Delta t_{1/2}$ but for slow durations $\Delta t_{1/3}$ the fitting line inclination decreases with simultaneous decreasing correlation coefficient r and probability P . ICME-induced storms have low values of line inclination, correlation coefficient and probability for both types of recovery durations, i.e. there is no dependence between the storm development rate and both fast and slow durations.

4. Discussion

In accordance with formula by *Burton et al.* [1975] in the case of neglecting the term related to the decay of the ring current at the main phase and numerous papers (see, e.g., *Kane* [2010]; *Ontiveros* [2010]; *Yermolaev et al.* [2010]; *Weigel* [2010]; *Nikolaeva et al.* [2013, 2014]), for various interplanetary drivers the measured and density-corrected Dst and Dst^* indexes may be approximated by a linear function of the integral of interplanetary convective electric field E_y with high accuracy (the correlation coefficients are

0.98-0.99), i.e. derivative of Dst index is proportional to electric field E_y : $dDst/dt = CE_y$. As approximate equality $Dst_{min}/\Delta T \approx dDst/dt = CE_y$ is fair, the obtained results give the indirect indications in favor of a hypothesis that the durations of recovery for magnetic storms induced by CIR and Sheath correlate with the average electric field during main phase $\langle E_y \rangle$.

Reduction of correlation for slow recovery duration $\Delta t_{1/3}$ for CIR-induced storms can be explained by the fact that at the second part of recovery phase the external factors start prevailing over internal magnetospheric processes, and the high-speed solar wind after CIR is characterized by higher level of disturbances of plasma and magnetic field parameters (see, e.g., [Hajra *et al.*, 2014]), than in the ICMEs after Sheath.

As we showed earlier ([Nikolaeva *et al.*, 2013]), the interplanetary-magnetospheric coupling coefficient between the derivative of Dst index and average electric field $\langle E_y \rangle$ depends on the driver type. Therefore the lower correlation in Figure 2 for ICME-induced storms than for CIR/Sheath-induced storms can be connected with lower coupling coefficients for MC/Ejecta-induced storms in comparison with coupling coefficients for CIR/Sheath-induced storms.

5. Conclusions

We analyzed the temporal profiles of Dst index for magnetic storms induced by various types of interplanetary drivers: compression regions CIR (85 storms) and Sheath (71), and bodies of interplanetary CME (158). In addition to our previous paper [Yermolaev *et al.*, 2014] where we compared the durations of main phase ΔT and the short and long durations of recovery phase $\Delta t_{1/2}$ and $\Delta t_{1/3}$ (respectively, at the levels of $1/2Dst_{min}$

and $1/3Dst_{min}$), here we study the dependences of the development rate $Dst_{min}/\Delta T$ on recovery phase durations $\Delta t_{1/2}$ and $\Delta t_{1/3}$. Obtained results allows us to make following conclusions.

1. The storm development rate $Dst_{min}/\Delta T$ correlates with both short $\Delta t_{1/2}$ and long $\Delta t_{1/3}$ durations for Sheath-induced storms.
2. The storm development rate $Dst_{min}/\Delta T$ correlates with only short duration $\Delta t_{1/2}$ and does not correlate with long $\Delta t_{1/3}$ duration for CIR-induced storms. The absence of correlation with long duration may be connected with high variability of solar wind and IMF parameters in the high-speed streams after CIR regions (see, e.g., [Hajra *et al.*, 2014]), in contrast with smooth changing parameters in ICME bodies after Sheath regions.
3. These results allow us to suggest that the physical processes of formation and decay of storm activity in the magnetosphere are similar for CIR- and Sheath-induced storms.
4. There is no correlation between the storm development rate $Dst_{min}/\Delta T$ and short and long durations of recovery phase for ICME-induced storms.
5. The magnetosphere processes, which are responsible for storm activity, are suggested to be different for ICME- and CIR/Sheath-induced storms. This may be connected with various interplanetary-magnetospheric coupling coefficients for different interplanetary drivers ([Nikolaeva *et al.*, 2013]).

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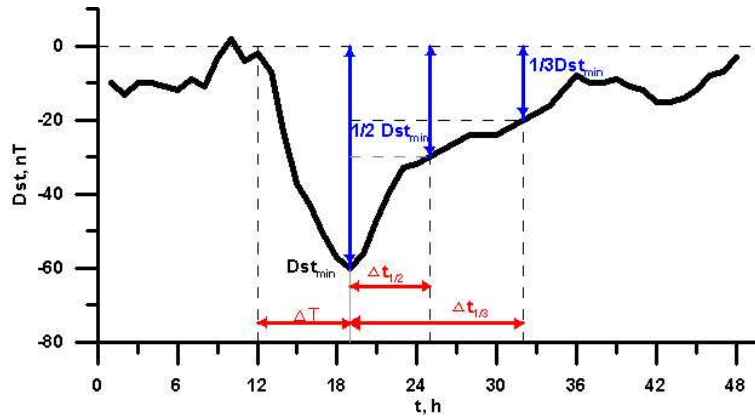


Figure 1. Schematic view of method for determination of durations of main and recovery phases for magnetic storms

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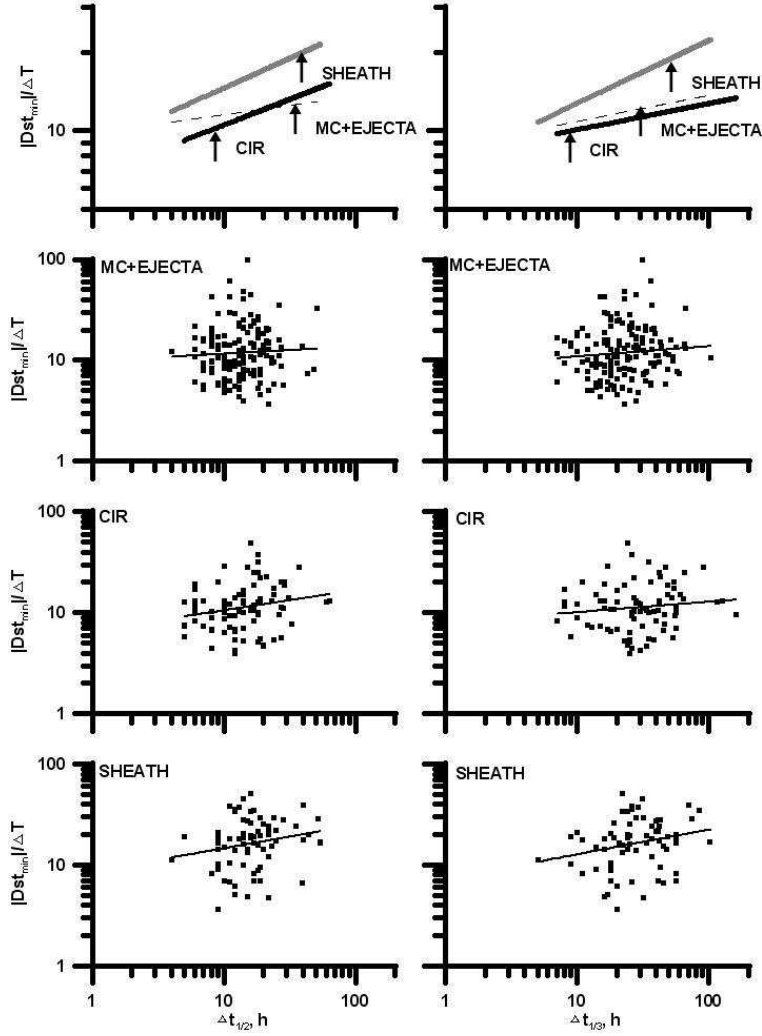


Figure 2. Relations between the storm development rate $Dst_{min}/\Delta T$ and recovery phase durations $\Delta t_{1/2}$ and $\Delta t_{1/3}$ for magnetic storms generated by CIR, Sheath and ICME (MC+Ejecta)

Table 1. The correlation coefficients r , probability P and fitting lines for relations between the storm development rate $Dst_{min}/\Delta T$ and recovery phase durations $\Delta t_{1/2}$ and $\Delta t_{1/3}$ for magnetic storms generated by CIR, Sheath and ICME (MC+Ejecta) in Figure 2

SW type	N	$\Delta t_{1/2}$ ^a				$\Delta t_{1/3}$ ^b			
		r	P	W	Fitting equation	r	P	W	Fitting equation
Sheath	71	0.20	0.90	1.67	$\ln y = 0.23 \ln x + 2.15$	0.23	0.95	1.97	$\ln y = 0.24 \ln x + 1.99$
CIR	85	0.21	0.94	1.90	$\ln y = 0.20 \ln x + 1.90$	0.15	0.73	1.10	$\ln y = 0.10 \ln x + 2.08$
ICME ^c	158	0.05	0.49	0.66	$\ln y = 0.07 \ln x + 2.28$	0.09	0.72	1.09	$\ln y = 0.10 \ln x + 2.15$

^a $\Delta t_{1/2} = t(1/2Dst_{min}) - t(Dst_{min})$

^b $\Delta t_{1/3} = t(1/3Dst_{min}) - t(Dst_{min})$

^c ICME is MC + Ejecta